

SPATIOTEMPORAL VARIABILITY, EMISSION SOURCES AND METEOROLOGICAL CONTROLS OF PM_{2.5} AND PM₁₀ IN DELHI, PUNJAB, HARYANA AND CHANDIGARH: A COMPARATIVE REVIEW (2018–2026)

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ABSTRACT

Delhi, Chandigarh, Haryana and Punjab lie in the north-western Indo-Gangetic Plain (IGP), one of the most polluted regions in the world. This review synthesizes outdoor PM_{2.5} and PM₁₀ evidence for these four jurisdictions published between 2018 and 2026, drawing on national monitoring analyses, city-level records for Delhi and Chandigarh, and state-wide, district and site-level studies for Punjab and Haryana. Across the jurisdictions reviewed, mean PM_{2.5} ranged from about 51 to 118 µg/m³ and PM₁₀ from about 76 to 225 µg/m³ – 1.3–3.0 and 1.3–3.8 times the national standards – and no city, district or network mean met either annual standard. In Delhi, PM_{2.5} averaged 83–101 µg/m³ and PM₁₀ 164–225 µg/m³ during 2018–2024 (CPCB January–November means), with 157–206 “poor” to “severe” AQI days a year and no sustained decline after 2020. Punjab's two continuous sites averaged 58–73 µg/m³ PM_{2.5} over 2017–2023, below Delhi's 105–118 µg/m³, but Ludhiana was the only monitored site in the four jurisdictions with a significant upward trend (almost 10% a year). Haryana's district monitoring data for 2019–2024 averaged 64 µg/m³ PM_{2.5} and 145 µg/m³ PM₁₀; at least 20 of 23–24 locations exceeded the annual PM_{2.5} standard every year from 2021, and the NCR hotspots of Gurugram, Faridabad and Charkhi Dadri (85–95 µg/m³) now approach Delhi. Even Chandigarh, a planned city with extensive green cover, recorded annual PM₁₀ of 76.2 µg/m³ in 2020 and 91.7 µg/m³ in 2021 at its Sector 25 station, above the 60 µg/m³ standard, with October peaks of about 121–125 µg/m³ during paddy-residue burning. During the 2020 COVID-19 lockdown, PM_{2.5} fell by about 43% in Punjab relative to the pre-lockdown weeks and by 57% in Haryana relative to the same period of 2019; this indicates a large anthropogenic share, although favourable spring meteorology also contributed, and Haryana's PM₁₀ in the same spring window had returned to its pre-pandemic level by 2022. Winter meteorology, crop-residue burning, traffic, industry and dust drive these patterns, and nearly half of Haryana's PM is transported from outside the state. We conclude that sustained improvement in northern Indian air quality requires airshed-wide coordination across Delhi, Punjab, Haryana and Chandigarh, enforcement of NCAP city plans, alternatives to stubble burning and expanded monitoring beyond large cities.

KEYWORDS: Particulate matter; PM_{2.5}; PM₁₀; ambient air quality; northern India; Indo-Gangetic Plain; Delhi; Punjab; Haryana; Chandigarh; NO₂; SO₂; NH₃; O₃; COVID-19 lockdown; NCAP.

1. INTRODUCTION

Air pollution is the contamination of the atmosphere by gases, particulate matter, smoke and other substances that adversely affect human health, vegetation, animals and the wider environment. It is among the most serious environmental and public-health problems in India, where rapid urbanisation, industrialisation and growth in vehicle numbers have outpaced emission controls [1]. A large share of the world's population, and virtually the entire population of northern India, lives where pollution exceeds the World Health Organization (WHO) guideline values [2]. Mean PM_{2.5} in Delhi and across Haryana's districts during 2018–2024, and at Punjab's continuous sites during 2017–2023, remained 1.3–3.0 times the national standard of 40 µg/m³ [3–5], and Delhi's annual average of about 90 µg/m³ is nearly 20 times the WHO guideline of 5 µg/m³ [6]. Of all outdoor air pollutants, PM_{2.5} poses the greatest threat to health [6].

Air pollutants originate from both natural and anthropogenic sources. In northern India the principal anthropogenic sources are vehicular exhaust, road-dust resuspension, industry, brick kilns, thermal power plants, construction and seasonal crop-residue burning [4,5]. Among these pollutants, fine particulate matter (PM_{2.5}) poses the greatest threat to health, because it can penetrate deep into the lungs and enter the bloodstream [6].

1.1 Particulate matter: size classes, sources and composition

PM is classified by aerodynamic diameter. PM₁₀ (≤ 10 µm), the inhalable coarse fraction, is dominated by mechanically generated particles such as road dust, construction dust and transported desert dust [4,7]. PM_{2.5} (≤ 2.5 µm), the fine fraction, is dominated by combustion products and by secondary aerosol formed in the atmosphere from nitrogen oxides, sulphur dioxide, ammonia and volatile organic compounds [7]. PM_{2.5} can penetrate deep into the lungs and enter the bloodstream [6], whereas PM₁₀ mainly affects the respiratory system [1]. Table 1 summarises the main characteristics of the two fractions.

Table 1. Comparative characteristics of PM_{2.5} and PM₁₀ (compiled from [1,2,4,6–8]).

Attribute	PM _{2.5} (fine)	PM ₁₀ (inhalable coarse + fine)
Aerodynamic diameter	≤ 2.5 µm	≤ 10 µm (includes PM _{2.5})
Dominant sources in northern India	Vehicle exhaust, residential solid-fuel burning, crop-residue burning, industry and power plants, secondary aerosol	Road and construction dust, transported desert dust, industry
Typical composition	Organic aerosol, black carbon, sulphate, nitrate, ammonium	Mineral dust, plus the fine fraction
Health relevance	Penetrates deep into the lungs; can enter the bloodstream	Inhalable; affects the respiratory system
Indian NAAQS (annual / 24-h)	40 / 60 µg/m ³	60 / 100 µg/m ³
WHO 2021 AQG (annual / 24-h)	5 / 15 µg/m ³	15 / 45 µg/m ³

1.2 The north-western Indo-Gangetic Plain

The IGP is a contiguous airshed that includes Punjab, Haryana and Delhi and is home to more than 40% of India's population [3]. Its geography – a flat basin bounded by the Himalaya to the north – combined with dense population, intensive agriculture and industrial growth makes it one of the most polluted regions in the world [1]. Pollution here is a regional problem: in Haryana, an estimated 30% of PM originates outside the state and a further 15% outside India [9], while in Delhi, sources in neighbouring NCR districts contributed about 35% of pollution in October–November 2024, against about 30% from Delhi's own sources [10]. Post-monsoon burning of paddy residue in Punjab and Haryana adds a large seasonal pulse that is transported downwind to Delhi [5,7]. Reported paddy-residue fire counts fell steeply after 2021 – from 71,304 to 9,655 in Punjab and from 6,987 to 1,118 in Haryana between 2021 and 2024 [10] – yet during the October–November 2019 burning season crop-residue burning still contributed about 50% of surface PM_{2.5} in Punjab, 36% in Haryana and 13% in Delhi-NCR [7]. Airshed modelling for 2019–2020 shows how tightly these states are linked: restricting crop-residue burning across Punjab, Haryana and Delhi-NCR lowered PM_{2.5} during peak burning by about 45% in Punjab and 35% in Haryana, and even controls confined to Delhi-NCR reduced it by about 26% in Haryana and 10% in Punjab [7]. Figure 1 summarises the sources and atmospheric processes that govern ambient PM in the region.

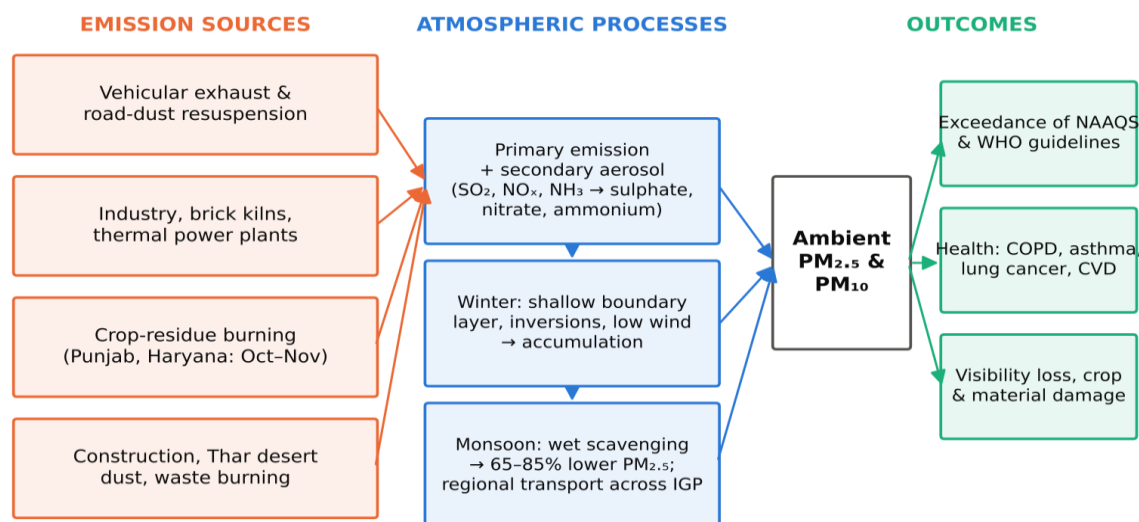


Figure 1. Conceptual framework of outdoor particulate pollution in northern India: emission sources, atmospheric processes (secondary aerosol formation, winter accumulation, monsoon washout and regional transport) and outcomes.

India's monitoring network has expanded markedly since NCAP began in 2019. Between 2019 and 2023 the number of continuous monitoring stations rose from 24 to 30 in Haryana, while Delhi (40–41) and Punjab (8) changed little [11]; nationally, the National Air Quality Monitoring Programme now operates 804 stations across 344 cities [4]. Coverage nevertheless remains uneven: most NCAP cities still rely on a single station, so city-level means carry substantial uncertainty, and Punjab's network has not grown despite the state's role in post-monsoon pollution [11].

1.3 Health and environmental effects

Exposure to PM_{2.5} and PM₁₀ increases the risk of chronic obstructive pulmonary disease (COPD), lung cancer, heart disease, stroke and pneumonia [3], and is also linked to neuroinflammation and mental-health disorders [6]. Children and young people are among the most vulnerable, because their respiratory and immune systems are still developing [6]. Particulate pollution also impairs visibility and affects ecosystems, agricultural productivity and transport operations [7].

1.4 Scope and objectives

This review focuses exclusively on outdoor (ambient) PM in northern Indian states and on evidence published between 2018 and 2026. Its objectives are to (i) quantify regional PM_{2.5} and PM₁₀ levels and compliance with standards across northern India, (ii) compare Delhi, Punjab, Haryana and Chandigarh at state and city level, (iii) examine seasonal patterns, multi-year trends and the 2020 COVID-19 lockdown, and (iv) evaluate sources, health implications and policy responses.

2. MATERIALS AND METHODS

2.1 Review approach and inclusion criteria

Studies were included if they (a) were published between 2018 and 2026, (b) reported outdoor ambient PM_{2.5} and PM₁₀ data, and (c) covered northern Indian states or presented separable values for northern India. Studies of indoor air, studies published before 2018, studies outside India and values for southern Indian cities were excluded. Eleven studies met these criteria (Table 2), including a 2025 preprint for Delhi that was used only for its compiled 2018–2024 AQI, fire-count and source-share data, and a national multi-site analysis whose record (2017–2023) is reported with its period stated. For Delhi, only observations from 2018 onwards were retained, consistent with the 2018–2026 scope. Studies whose data pre-date 2018, such as a 2016–2018 Delhi health study [12], were used only for background and interpretation, not in the results tables. Quantitative data – annual and seasonal means, exceedance counts, trends and lockdown changes – were extracted from text and tables, expressed in µg/m³ and compared with the CPCB National Ambient Air Quality Standards (NAAQS) [8] and WHO 2021 guidelines [2] (Figure 2). Where national studies reported both northern and southern India, only northern values were retained. In addition to these core datasets, further peer-reviewed studies published in 2018–2026 on health burden, crop-residue burning, source contributions and lockdown effects in northern India were consulted to support interpretation; these are cited in the relevant sections but were not used to build the comparative tables.

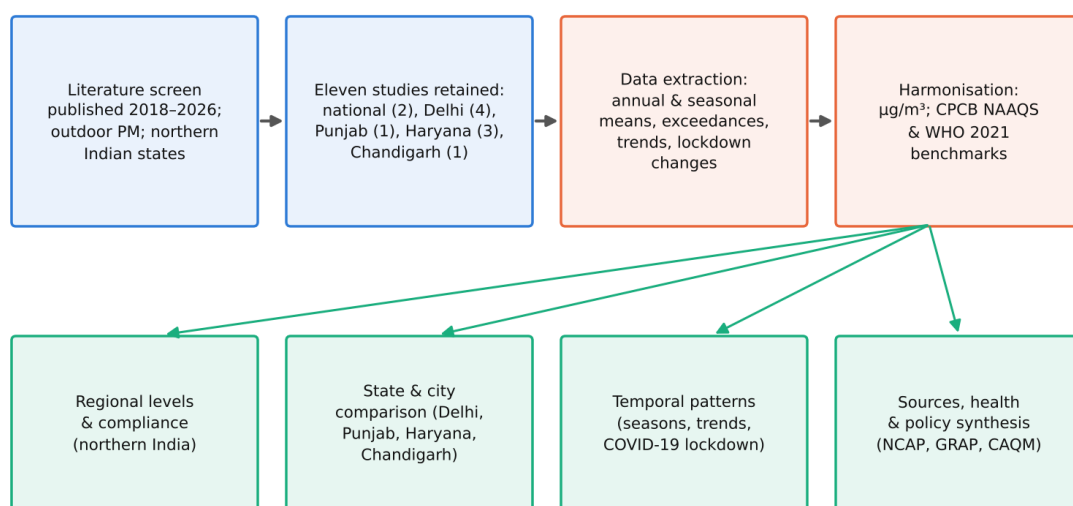


Figure 2. Framework of the review: screening, data extraction and harmonisation, and the four axes of synthesis.

Table 2. Studies synthesised in this review (all published 2018–2026).

Study	Region & data period	Data source / method	Pollutants	Principal finding
Guttikunda et al. (2025) [11]	India, 131 NCAP cities including the northern IGP; 2019–2023	CPCB continuous and manual stations; annual averages; AQI bulletins; satellite AOD	PM _{2.5} , PM ₁₀ , AQI	Cities above 120 µg/m ³ PM _{2.5} fell from 30% to 20%; mean AQI 132 → 113
Ghosh et al. (2026) [5]	India, 29 continuous sites; Delhi, Punjab and Haryana sites used here; 2017–2023	CPCB and US Embassy monitors; Mann–Kendall trends; PCA; HYSPLIT back-trajectories	PM _{2.5}	Delhi sites 105–118 µg/m ³ ; Punjab 58–73 µg/m ³ ; Haryana 54–84 µg/m ³ ; Ludhiana rising ~10%/yr
Verma & Singh (2026) [4]	Delhi; 2018–2024	CPCB, DPCC and PIB/MoEFCC records; GIS hotspot mapping; policy review	PM _{2.5} , PM ₁₀ , AQI	PM _{2.5} 83–101 µg/m ³ (Jan–Nov); 157–206 poor-to-severe AQI days/yr

Study	Region & data period	Data source / method	Pollutants	Principal finding
Tewari & Jindal (2025) [10]	Delhi; 2018–2024 (AQI and fire-count data used)	Compiled AQI, fire-count and source-share data; correlation analysis (preprint)	AQI, PM ₁₀ , PM _{2.5}	November AQI 312–377; farm fires ~8% of pollution (Oct–Nov 2024); weak AQI–fire link
Nandi et al. (2026) [7]	NCT-Delhi and NW IGP airshed; Sep 2019–Jan 2020	WRF-Chem emission-perturbation and source-apportionment modelling	PM _{2.5} and components	Residential ~53% of PM _{2.5} ; airshed-wide controls –36% vs –2 to –3% for NCR-only crop-burning ban
Bwire et al. (2026) [6]	Delhi (and Dhaka); Jan and Mar 2025	Real-time IQAir PM _{2.5} linked to online survey (Delhi n = 365)	PM _{2.5}	Daily PM _{2.5} 171–182 µg/m ³ ; itchy eyes 34% → 69%, respiratory difficulty 44% → 63%
Chaudhry et al. (2025) [13]	Punjab, 8 stations; Mar–Jun 2020	CPCB/PPCB stations; NAQI; ANOVA	PM _{2.5} , PM ₁₀ , NO ₂ , CO, NH ₃ , SO ₂ , O ₃	Lockdown: PM –43 to –45%; NAQI up to –65%
Rahul (2026) [3]	Haryana, 24 locations; 2019–2024	District-wise annual means; comparison with Delhi	PM _{2.5} , PM ₁₀	NCR districts approaching Delhi levels
Vyas et al. (2026) [1]	Haryana, 10 constituencies; 2019–2022	CPCB CAAQMS; lockdown-phase comparison	PM _{2.5} , PM ₁₀ , NO _x , CO, O ₃	PM _{2.5} –57% in lockdown phase 1; rebound by 2022
Manjeet et al. (2022) [14]	Haryana, 22 districts; Mar–May 2019 and 2020	CPCB data; district AQI; GIS mapping	PM ₁₀ , PM _{2.5} , O ₃ , NO _x , SO ₂ , CO (AQI)	District AQI improved by up to 71–80% in lockdown; Faridabad poor → satisfactory
Kaur et al. (2022) [15]	Chandigarh, Sector 25; 2020–2021	CPCC continuous station; monthly and seasonal means; meteorology	PM ₁₀	Annual 76.2 and 91.7 µg/m ³ ; October peaks > 120 µg/m ³

2.2 Air quality standards and index

Table 3 compares the Indian NAAQS with WHO 2021 guidelines. India's National Air Quality Index (NAQI) computes a sub-index for each pollutant by linear interpolation between concentration breakpoints and reports the highest sub-index as the overall NAQI; at least three pollutants, including PM_{2.5} or PM₁₀, are required (Table 4) [13].

Table 3. Indian National Ambient Air Quality Standards and WHO 2021 air quality guidelines.

Pollutant	Averaging time	CPCB NAAQS (industrial, residential, rural)	CPCB NAAQS (ecologically sensitive)	WHO 2021 AQG
PM ₁₀ (µg/m ³)	Annual 24 h	60 100	60 100	15 45
PM _{2.5} (µg/m ³)	Annual 24 h	40 60	40 60	5 15
NO ₂ (µg/m ³)	Annual 24 h	40 80	30 80	10 25
SO ₂ (µg/m ³)	Annual 24 h	50 80	20 80	– 40
O ₃ (µg/m ³)	8 h	100	100	100
CO (mg/m ³)	8 h	2	2	4 (24 h)

Sources: CPCB [8]; WHO [2].

Table 4. CPCB National Air Quality Index categories and PM breakpoints.

NAQI	Category	PM _{2.5} (µg/m ³) 24-h	PM ₁₀ (µg/m ³) 24-h	Likely health impact
0–50	Good	0–30	0–50	Minimal
51–100	Satisfactory	31–60	51–100	Minor breathing discomfort to sensitive people
101–200	Moderate	61–90	101–250	Discomfort to people with lung or heart disease
201–300	Poor	91–120	251–350	Discomfort to most people on prolonged exposure
301–400	Very poor	121–250	351–430	Respiratory illness on prolonged exposure
401–500	Severe	> 250	> 430	Affects healthy people; serious impact on those with disease

Source: CPCB NAQI scheme as described in [13].

2.3 Study region

Delhi. The National Capital Territory has a semi-arid climate with hot summers, cold foggy winters and moderate monsoon rainfall. It lies in the IGP and is surrounded on three sides by Haryana. It covers 1,483 km², of which 1,114 km² is urban and 369 km² rural. Air quality is monitored by the Delhi Pollution Control Committee (DPCC; 26 real-time stations), CPCB, SAFAR and the India Meteorological Department, and in 2018 the Delhi Government identified 13 pollution hotspots where continuous stations recorded PM₁₀ above 300 µg/m³ and PM_{2.5} above 100 µg/m³ [4].

Punjab. Punjab (29°32'–32°28' N, 73°50'–77°00' E; 50,362 km²) lies in the IGP at 180–500 m elevation, with a semi-arid climate (winter 1–10 °C; summer 42–48 °C) and more than 80% of its rainfall in the monsoon [13]. The Punjab–Haryana plain has a monsoon-type climate with dry, cold winters, very hot summers and hot, dry winds in May–June [5]. Continuous PM_{2.5} records with consistent coverage are available for Ludhiana and for Mandi Gobindgarh, a small town between Ludhiana and Chandigarh [5].

Haryana. Haryana (27°39'–30°35' N, 74°28'–77°36' E; 44,212 km²) surrounds Delhi on three sides, and 14 of its 22 districts lie within the National Capital Region (NCR). Its 22 districts cover 1.3% of India's area and fall into an eastern agro-climatic zone (including Panchkula, Ambala, Karnal, Panipat, Sonapat and Faridabad) and a western zone (including Sirsa, Hisar, Bhiwani and Mahendragarh), with rapid industrial and transport growth around the NCR hubs of Gurugram and Faridabad [14]. Annual rainfall varies from about 200 to 1,400 mm and temperatures from 1 to 45 °C [3].

Chandigarh. The Union Territory of Chandigarh (30°44' N, 76°47' E; 114 km²) is the shared capital of Punjab and Haryana and forms a tricity with Mohali (Punjab) and Panchkula (Haryana). It had about 1.05 million residents in 2011 (9,258 persons/km²), a humid subtropical climate with hot summers and cold dry winters, and the highest vehicle density in India [15]. The Chandigarh Pollution Control Committee operates continuous monitoring stations, including one in Sector 25 [15]. Although the city is noted for its planned layout and green cover, its PM₁₀ peaks in October, the paddy-residue burning month in the surrounding states [15].

3. RESULTS

3.1 Regional overview: northern India

Particulate matter dominates the pollutant mix across northern India throughout the review period (Table 5, Figure 3). In every dataset reviewed for Delhi, Punjab, Haryana and Chandigarh, city, district or network means exceeded the annual PM_{2.5} and PM₁₀ standards. Mean PM_{2.5} ranged from about 51–73 µg/m³ across Haryana's districts (yearly averages, 2019–2024) and 58–73 µg/m³ at Punjab's two continuous sites (2017–2023) to 83–118 µg/m³ in Delhi – 1.3 to 3.0 times the NAAQS of 40 µg/m³ and 10 to 24 times the WHO guideline [3–5]. PM₁₀ was 1.3 to 3.8 times its annual standard, from about 76–92 µg/m³ in Chandigarh to 164–225 µg/m³ in Delhi [3,4,15]. At national level, a review of NCAP cities for 2019–2023 found that the share of cities with annual PM_{2.5} above 120 µg/m³ fell from 30% to 20%, but more than half remained between 60 and 120 µg/m³, half stayed above 150 µg/m³ PM₁₀, and the mean AQI fell only from 132 to 113 [11]. Because most of these cities operate a single monitoring station, city means carry substantial uncertainty [11].

Table 5. Range of mean PM_{2.5} and PM₁₀ (µg/m³) reported for Delhi, Chandigarh, Haryana and Punjab, 2017–2024.

Jurisdiction and dataset	Period	PM _{2.5}	PM ₁₀	PM _{2.5} annual NAAQS ÷	PM ₁₀ annual NAAQS ÷
Delhi, CPCB means for 1 Jan–18 Nov [4]	2018–2024	82.8–100.5	163.7–225.3	2.1–2.5	2.7–3.8
Delhi, annual means [3]	2019–2024	95.0–108.0	180.0–217.0	2.4–2.7	3.0–3.6
Delhi, four continuous sites [5]	2017–2023	105–118	–	2.6–3.0	–

Jurisdiction and dataset	Period	PM _{2.5}	PM ₁₀	PM _{2.5} annual NAAQS ÷	PM ₁₀ annual NAAQS ÷
Punjab: Ludhiana and Mandi Gobindgarh [5]	2017–2023	58–73	–	1.5–1.8	–
Haryana, yearly mean of district values [3]	2019–2024	51.1–73.0	134.7–157.3	1.3–1.8	2.2–2.6
Haryana NCR districts, reported average [3]	2019–2024	47.0–103.0	82.1–196.0	1.2–2.6	1.4–3.3
Haryana: Rohtak and Panchkula [5]	2017–2023	54–84	–	1.4–2.1	–
Chandigarh, Sector 25 continuous station [15]	2020–2021	–	76.2–91.7	–	1.3–1.5

Ranges are the lowest and highest annual (or multi-year site) means reported for each dataset; ratios computed by the present authors against the annual NAAQS (40 µg/m³ for PM_{2.5}; 60 µg/m³ for PM₁₀). Haryana yearly means were computed by the present authors from the district values in [3]. – = not reported.

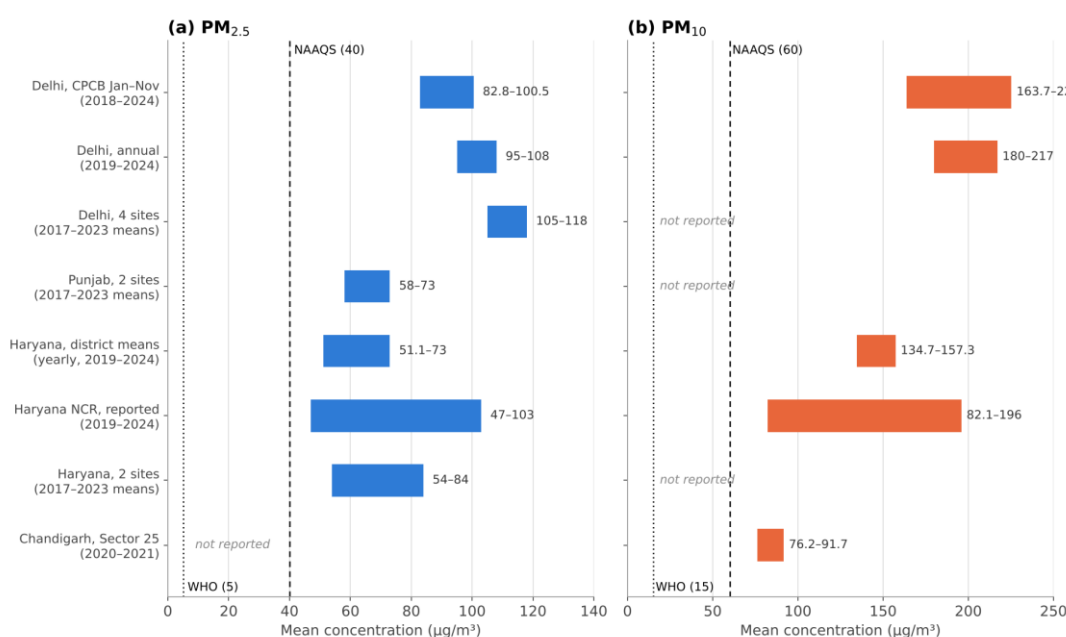


Figure 3. Range of mean PM_{2.5} and PM₁₀ reported for Delhi, Chandigarh, Haryana and Punjab (2017–2024), against the annual NAAQS and WHO 2021 guidelines. Bars span the lowest to highest mean in each dataset. Data: Rahul [3]; Verma and Singh [4]; Kaur et al. [15]; Ghosh et al. [5].

3.2 Delhi

Delhi remains the reference point for particulate pollution in northern India (Table 6, Figure 4). CPCB records compiled by Verma and Singh [4] show that mean PM_{2.5} for 1 January–18 November fell from 100.5 µg/m³ in 2018 to 98.4 µg/m³ in 2019 and 82.8 µg/m³ in the 2020 lockdown year, and then stayed between 86.1 and 94.3 µg/m³ during 2021–2024. PM₁₀ followed the same course, falling from 225.3 to 163.7 µg/m³ between 2018 and 2020 and returning to 187.9–200.5 µg/m³ thereafter. Both pollutants rose again in 2024 after the lowest non-lockdown values in 2023. Because these averages end before the late-November and December peak, full-year means are higher: Rahul [3] reports annual PM_{2.5} of 95–108 µg/m³ and PM₁₀ of 180–217 µg/m³ for 2019–2024. On either basis, PM_{2.5} remained 2.1–2.7 times the annual NAAQS and 17–22 times the WHO guideline, and PM₁₀ 2.7–3.8 times its annual standard, in every year from 2018 to 2024. The number of days in the “poor” to “severe” AQI categories (AQI > 200) fell from 206 in 2018 to 183 in 2019 and 139 in 2020, returned to 202 in 2022, and declined to 159 in 2023 and 157 in 2024; correspondingly, “good” to “moderate” days rose from 159 in 2018 to 209 in 2024, the highest count since 2020 [4]. Monthly AQI shows a consistent winter maximum and monsoon minimum: November was the most polluted month on average during 2018–2024 (mean AQI 346; range 312–377) and August the cleanest (mean 93; range 64–116) [4,10]. January 2024 had the highest January AQI of the period (355) under calm winds, May 2024 the worst May (223) after a prolonged dry, dusty spell, and November 2024 an AQI of 374, with the highest daily AQI of the preceding four years on 18 November [4]. Monthly mean PM_{2.5} reached 165 µg/m³ in January 2025 [4], and continuous monitoring recorded daily PM_{2.5} of 182 and 171 µg/m³ on 9 and 10 January 2025, compared with about 35 µg/m³ on 15 March 2025 [6].

The relative weight of sources has shifted over the review period. According to a 2025 preprint that compiles official fire-count and AQI data, paddy-residue fire counts fell from 71,304 in 2021 to 9,655 in 2024 in Punjab and from 6,987 to

1,118 in Haryana, yet Delhi's November AQI did not improve, and AQI was only weakly correlated with stubble burning [10]. CPCB decision-support estimates show that the daily share of stubble burning in Delhi's PM_{2.5} stayed below 2% until about 20 October 2024, ranged from about 15% to 33% between 1 and 23 November (peak 33.3% on 14 November), and fell below 6% by late November; in 2023 it peaked at 29% on 6 November and remained below 10% after mid-November [4]. The same preprint, citing a Centre for Science and Environment analysis, reports that for 12 October–3 November 2024 sources in neighbouring NCR districts contributed about 35% of Delhi's pollution, Delhi's own sources about 30% and farm fires about 8%; vehicles accounted for 51.5% of the local share and dust for 3.7% [10]. Source-resolved modelling for September 2019–January 2020 gives a complementary picture [7]. Residential (household solid-fuel) emissions were the largest single contributor to PM_{2.5} over NCT-Delhi (about 53%), followed by transport (about 13%), industry (about 6%) and energy (about 5%), while crop-residue burning contributed about 13% over Delhi-NCR in October–November. Secondary aerosol made up about 55% of PM_{2.5} in the post-monsoon season and 58% in winter, and organic aerosol about 55% of the mass. A complete crop-burning ban confined to Delhi-NCR lowered NCT-Delhi PM_{2.5} by only 2.3% (2.8% in October–November), against 6.6% (8.0%) when applied across Punjab, Haryana and Delhi-NCR. Halving residential, transport and industrial emissions together with a crop-burning ban reduced PM_{2.5} by 24% when confined to the NCR and by about 36% across the airshed, and an airshed-wide crop-burning ban combined with halved residential emissions cut “very poor” days in the 153-day study period from 67 to 36 [7]. These concentrations have measurable short-term effects. Among 365 children, young people and parents surveyed in Delhi, reports of itchy eyes rose from 34% on a good-air day to 69% on high-pollution days, respiratory difficulty from 44% to 63%, diarrhoea or vomiting from 28% to 68% and low mood from 58% to 72%, while the share achieving at least 60 minutes of daily physical activity fell from 42% to 17% [6].

Table 6. Particulate matter and AQI indicators for Delhi, 2018–2024.

Year	PM _{2.5} CPCB Jan–18 Nov	PM ₁₀ CPCB Jan–18 Nov	PM _{2.5} annual mean	PM ₁₀ annual mean	Poor to severe days (AQI > 200)	Good to moderate days (AQI ≤ 200)	November mean AQI
2018	100.5	225.3	–	–	206	159	335
2019	98.4	208.6	108.0	217.0	183	182	312
2020	82.8	163.7	95.0	180.0	139	227	328
2021	91.8	195.3	105.0	210.0	168	197	377
2022	88.5	199.8	98.0	211.0	202	163	320
2023	86.1	187.9	100.9	205.0	159	206	373
2024	94.3	200.5	104.7	214.3	157	209	374

Values in µg/m³ unless stated. Sources: Verma and Singh [4] (CPCB means for 1 January–18 November of each year; AQI-day counts and monthly AQI from PIB/MoEFCC); Rahul [3] (annual means). The January–November means exclude most of the late-November–December peak and are therefore lower than full-year means. – = not reported.

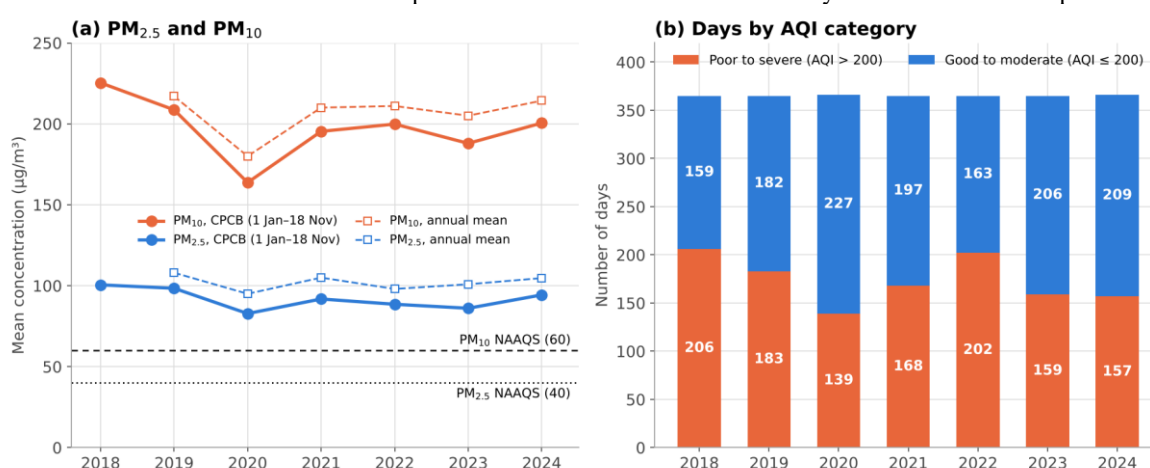


Figure 4. Delhi, 2018–2024: (a) mean PM_{2.5} and PM₁₀ from CPCB records for 1 January–18 November of each year (solid lines) and reported annual means (dashed lines), against the annual NAAQS; (b) number of days in the “poor” to “severe” (AQI > 200) and “good” to “moderate” (AQI ≤ 200) categories. Data: Verma and Singh [4]; Rahul [3].

3.3 Punjab

Continuous monitoring records for Punjab are sparse. In a national analysis of 29 sites for 2017–2023, mean PM_{2.5} was 73 µg/m³ at Mandi Gobindgarh and 58 µg/m³ at Ludhiana – 1.8 and 1.5 times the annual NAAQS, but well below the four Delhi sites (105–118 µg/m³) (Table 7) [5]. Ludhiana was nevertheless the only site in Delhi, Punjab or Haryana with a statistically significant upward trend, rising by almost 10% a year (Mann–Kendall $\tau = 0.39$, $p < 0.01$), and the Punjab

sites, like those in Haryana, stayed at or above their pre-COVID (2017–2019) levels in 2021–2022 while most sites elsewhere declined [5]. Mandi Gobindgarh showed the widest day-to-day variability in the network (maximum 872 $\mu\text{g}/\text{m}^3$), and its levels were statistically indistinguishable from those at Rohtak [5]. Monthly means at the Punjab and Haryana sites peak in winter and again in April–May, when wheat residue is burned, and principal component analysis assigns a biomass-burning component whose highest loadings are at Ludhiana (0.8), Panchkula (0.7) and Rohtak (0.6) [5]. A network of 29 sensors across Punjab, Haryana and the NCR traced the 2022 burning season: $\text{PM}_{2.5}$ was below 60 $\mu\text{g}/\text{m}^3$ in early October, exceeded 200 $\mu\text{g}/\text{m}^3$ at many sites during the first two weeks of November and peaked near 500 $\mu\text{g}/\text{m}^3$ on 5–9 November, while two plumes above 500 $\mu\text{g}/\text{m}^3$ moved from Punjab across Haryana into the NCR on 2–3 and 9–11 November [16]. For the 2019 post-monsoon season, airshed modelling assigns about 50% of surface $\text{PM}_{2.5}$ across Punjab to crop-residue burning, roughly two-thirds of it as organic aerosol [7].

Table 7. $\text{PM}_{2.5}$ statistics ($\mu\text{g}/\text{m}^3$) at continuous monitoring sites in Punjab and Haryana, 2017–2023.

Site	State	Mean	Median	SD	Maximum	Trend (Mann–Kendall τ)	Biomass-burning PC loading
Mandi Gobindgarh	Punjab	73	67	52	872	No trend (0.09)	0.5
Ludhiana	Punjab	58	49	32	197	Increasing (0.39)*	0.8
MD University, Rohtak	Haryana	84	74	56	530	No trend (0.13)	0.6
Sector 6, Panchkula	Haryana	54	50	28	184	No trend (0.10)	0.7

Source: Ghosh et al. [5]. Statistics are from daily data; trends are from the Mann–Kendall test on deseasonalised monthly means (March 2017–March 2023), * $p < 0.01$. The loading is each site’s weight on the principal component that the authors attribute to biomass burning.

3.4 Haryana

Pooling the district annual means reported for 2019–2024 (140 district-years for $\text{PM}_{2.5}$ and 129 for PM_{10} gives an overall mean of 64.2 ± 22.3 $\mu\text{g}/\text{m}^3$ for $\text{PM}_{2.5}$ and 145.1 ± 52.4 $\mu\text{g}/\text{m}^3$ for PM_{10} – about 1.6 and 2.4 times the annual NAAQS (Table 8) [3]. Individual values ranged from 17.7 to 145 $\mu\text{g}/\text{m}^3$ for $\text{PM}_{2.5}$ and from 68 to 372.5 $\mu\text{g}/\text{m}^3$ for PM_{10} . District $\text{PM}_{2.5}$ and PM_{10} were essentially uncorrelated ($r = -0.06$), which is unexpected for two size fractions measured at the same locations and points to inconsistencies in the compiled data rather than to independent sources [3] (Section 4.6). Continuous sites analysed independently for 2017–2023 recorded mean $\text{PM}_{2.5}$ of 84 $\mu\text{g}/\text{m}^3$ at Rohtak, close to Delhi, and 54 $\mu\text{g}/\text{m}^3$ at Panchkula in the north of the state (Table 7) [5].

Table 8. Descriptive statistics of district annual mean $\text{PM}_{2.5}$ and PM_{10} ($\mu\text{g}/\text{m}^3$) across Haryana, 2019–2024.

Pollutant	District-years (n)	Mean	SD	Min.	Max.	Median	Annual NAAQS
$\text{PM}_{2.5}$	140	64.2	22.3	17.7	145.0	60.0	40
PM_{10}	129	145.1	52.4	68.0	372.5	133.0	60

Computed by the present authors from the district values reported by Rahul [3]; n = number of district-years with data. CPCB data for 2019–2020 place Haryana’s air quality in the “very poor” category in winter and the post-monsoon season of 2019, with a slight improvement in 2020, and in the “satisfactory” range in the monsoon and pre-monsoon months of both years, with the rabi half-year (October–March) consistently worse than the kharif half-year (April–September) [17]. Crop-residue burning is a major cause of this seasonal contrast [18]. In Gurugram, AQI records from four stations, including Sector 51 and Manesar, improved only slightly in parts of the city between 2019 and 2021 and remained at critical levels [19]. Year by year, the spread of district means narrowed after 2019 (Table 9): the highest $\text{PM}_{2.5}$ value fell from 145 $\mu\text{g}/\text{m}^3$ in 2019 to 90–105 $\mu\text{g}/\text{m}^3$ in 2020–2024, while the median dropped from 83 $\mu\text{g}/\text{m}^3$ in 2019 to 48 $\mu\text{g}/\text{m}^3$ in the 2020 lockdown year, recovered to 74 $\mu\text{g}/\text{m}^3$ in 2023 and eased to 60 $\mu\text{g}/\text{m}^3$ in 2024 [3]. Several 2019 values – such as 145 $\mu\text{g}/\text{m}^3$ at Panchkula and 140 $\mu\text{g}/\text{m}^3$ at Karnal, followed by 30 and 50 $\mu\text{g}/\text{m}^3$ in 2020 – are implausibly large swings and should be treated with caution (Section 4.6).

Table 9. Range, median and exceedances of district annual means ($\mu\text{g}/\text{m}^3$) across Haryana, 2019–2024.

Indicator	2019	2020	2021	2022	2023	2024
$\text{PM}_{2.5}$ range	17.7–145	30–90	38–100	38–95.3	25–90	20–104.7
$\text{PM}_{2.5}$ median	83.0	48.0	63.0	62.0	74.0	60.0
Locations > 40 $\mu\text{g}/\text{m}^3$	15/21	16/24	22/24	22/23	22/24	20/24
PM_{10} range	68–283	87–269	79–372.5	94–215	79–363	79–227

Indicator	2019	2020	2021	2022	2023	2024
PM ₁₀ median	133.0	157.0	128.8	124.0	134.0	126.0
Locations > 60 µg/m ³	23/23	18/18	22/22	21/21	22/22	23/23

Computed by the present authors from the district values reported by Rahul [3]; exceedances are locations above the annual NAAQS out of those reporting.

District-level data for 2019–2024 add further detail (Table 10) [3]. From 2021 onwards, 20 or more of the 23–24 locations reporting each year exceeded the annual PM_{2.5} standard. The highest multi-year means were in Gurugram (94.5 µg/m³, rising to 104.7 µg/m³ in 2024), Faridabad (89.9 µg/m³) and Charkhi Dadri (85.0 µg/m³), followed by Ballabgarh, Manesar and Bahadurgarh – all industrial or peri-urban NCR locations adjoining Delhi. Mandikhera (34.1 µg/m³) was the only location with a mean below the standard. Several locations deteriorated markedly after 2020: Rohtak rose from 34 to 65–85 µg/m³, Hisar from 40 to 64–83 µg/m³ and Yamunanagar from 38 to 60–80 µg/m³. Every reporting location exceeded the annual PM₁₀ standard of 60 µg/m³ in every year, with maxima of 363 µg/m³ in Gurugram (2023), 302 µg/m³ in Ballabgarh, 275 µg/m³ in Faridabad and 372.5 µg/m³ in Bhiwani (2021).

Table 10. Annual mean PM_{2.5} and PM₁₀ (µg/m³) at the most and least polluted Haryana locations, 2019–2024.

Location	PM _{2.5} 2019	PM _{2.5} 2022	PM _{2.5} 2024	PM _{2.5} mean	PM ₁₀ 2019	PM ₁₀ 2023	PM ₁₀ 2024
Most polluted (NCR industrial/peri-urban)							
Gurugram	94.0	–	104.7	94.5	163	363	186
Faridabad	94.5	95.3	84.0	89.9	171	275	227
Charkhi Dadri	94.0	78.0	78.0	85.0	137	82	137
Ballabgarh	96.9	80.0	60.0	75.3	168	302	168
Bahadurgarh	–	90.0	80.0	73.6	142	152	227
Least polluted							
Palwal	83.0	38.0	30.0	46.5	133	96	–
Sonipat	35.0	60.0	60.0	46.2	126	162	162
Mandikhera	17.7	52.0	20.0	34.1	193	–	137

Source: Rahul [3]; means computed by the present authors over available years. – = not reported.

3.5 Chandigarh

Chandigarh is often seen as one of the cleaner cities in the north, yet at its continuous station in Sector 25 annual PM₁₀ was 76.2 µg/m³ in 2020 and 91.7 µg/m³ in 2021 – above the 60 µg/m³ standard in both years – and increased by 20% as traffic restrictions were lifted [15].

Chandigarh shows strong seasonality. At Sector 25, monthly PM₁₀ peaked in October, the month of paddy-residue burning (120.8 µg/m³ in 2020 and 124.6 µg/m³ in 2021), and was lowest in August 2020 (33.9 µg/m³) and September 2021 (38.9 µg/m³) [15]. PM₁₀ there was inversely related to wind speed and relative humidity, and declined in the summer months as solar radiation increased [15]. In the 2017–2023 national analysis, the neighbouring tricity site at Panchkula averaged 54 µg/m³ PM_{2.5} and loaded strongly (0.7) on the biomass-burning component [5]. No source-apportionment study for Chandigarh based on data from 2018 onwards was identified.

3.6 Cross-state comparison

Comparing the three jurisdictions shows that high particulate levels extend across the north-western IGP (Figure 5). During 2019–2024, annual PM_{2.5} was 95–108 µg/m³ in Delhi and 84–105 µg/m³ in Gurugram and Faridabad, the two most polluted NCR districts of Haryana [3], whereas Punjab's two continuous sites averaged 58–73 µg/m³ over 2017–2023 [5]. On these data Delhi remains the most polluted of the three, Haryana's NCR belt follows closely, and Punjab's monitored sites are lower but, at Ludhiana, rising [3,5].

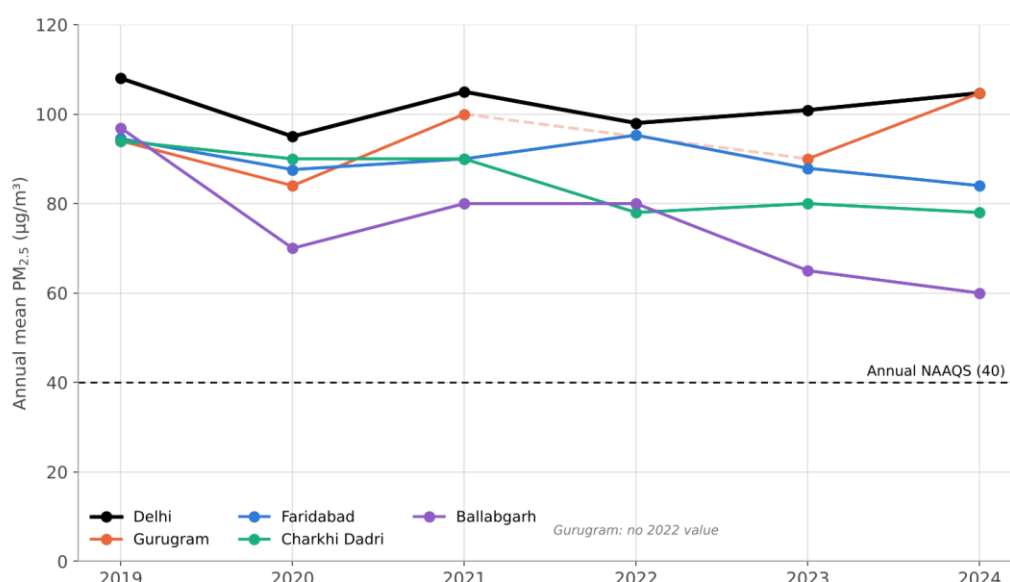


Figure 5. Annual mean PM_{2.5} in Delhi and four NCR districts of Haryana, 2019–2024. Data: Rahul [3].

Over 2019–2024, the reported average for Haryana's NCR districts increased from 47 to 103 $\mu\text{g}/\text{m}^3$ for PM_{2.5} and from 82 to 186 $\mu\text{g}/\text{m}^3$ for PM₁₀, whereas Delhi stayed within 95–108 $\mu\text{g}/\text{m}^3$ and 180–217 $\mu\text{g}/\text{m}^3$, respectively (Table 11, Figure 6) [3]. The two PM_{2.5} averages had converged by 2022 (97 $\mu\text{g}/\text{m}^3$ in Haryana and 98 $\mu\text{g}/\text{m}^3$ in Delhi). The 2019 Haryana value needs caution: it is well below the mean of the same study's district values for that year (about 73 $\mu\text{g}/\text{m}^3$) and was based on a smaller network, so part of the apparent increase reflects changes in station coverage. The reported averages for later years also differ from the district means in the same study (for example, 103 versus 61 $\mu\text{g}/\text{m}^3$ in 2024), so the reported series is best read as an NCR-weighted indicator rather than a state mean [3]. Both the reported averages and the district values nevertheless show NCR districts approaching Delhi, especially in winter [3].

Table 11. Reported average PM_{2.5} and PM₁₀ ($\mu\text{g}/\text{m}^3$) in Haryana's NCR districts and Delhi, 2019–2024.

Year	Haryana PM _{2.5}	Delhi PM _{2.5}	Haryana PM ₁₀	Delhi PM ₁₀	Haryana/Delhi (PM _{2.5})
2019	47.0	108.0	82.1	217.0	0.44
2020	83.3	95.0	83.3	180.0	0.88
2021	83.3	105.0	123.0	210.0	0.79
2022	97.0	98.0	159.0	211.0	0.99
2023	88.0	100.9	196.0	205.0	0.87
2024	103.0	104.7	186.0	214.3	0.98

Source: Rahul [3]; ratio computed by the present authors.

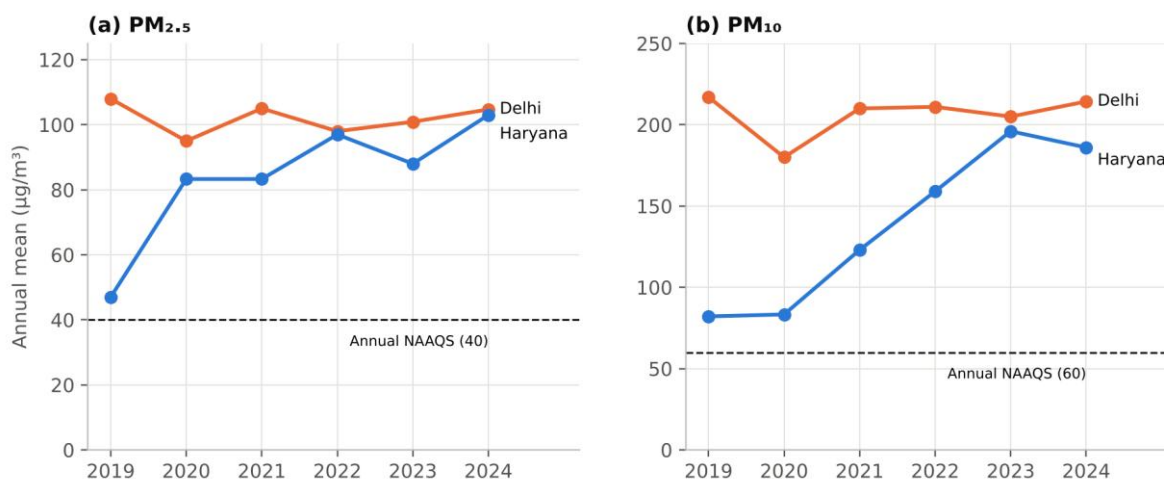


Figure 6. Reported annual average (a) PM_{2.5} and (b) PM₁₀ in Haryana's NCR districts and Delhi, 2019–2024. Data: Rahul [3].

Within the study region, the 2017–2023 national analysis ranks the four Delhi sites (105–118 $\mu\text{g}/\text{m}^3$) highest, followed by Rohtak (84 $\mu\text{g}/\text{m}^3$), Mandi Gobindgarh (73 $\mu\text{g}/\text{m}^3$), Ludhiana (58 $\mu\text{g}/\text{m}^3$) and Panchkula (54 $\mu\text{g}/\text{m}^3$), all above the annual

NAAQS (Table 12, Figure 7) [5]. Only one Delhi site, Dilshad Garden, showed a significant decline (about 5% a year), whereas Ludhiana rose significantly and the other Punjab and Haryana sites showed no significant trend [5].

Table 12. Mean PM_{2.5} (µg/m³) at continuous monitoring sites in Delhi, Haryana and Punjab, 2017–2023.

Site	State	Mean PM _{2.5}	Ratio to annual NAAQS	Trend, 2017–2023
NSIT Dwarka	Delhi	118	3.0	No trend
US Embassy, Chanakyapuri	Delhi	114	2.9	No trend
Shadipur	Delhi	112	2.8	No trend
IHBAS, Dilshad Garden	Delhi	105	2.6	Decreasing
MD University, Rohtak	Haryana	84	2.1	No trend
Mandi Gobindgarh	Punjab	73	1.8	No trend
Ludhiana	Punjab	58	1.5	Increasing
Sector 6, Panchkula	Haryana	54	1.4	No trend

Source: Ghosh et al. [5]; ratios computed by the present authors against the annual NAAQS (40 µg/m³). Trends from the Mann–Kendall test on deseasonalised monthly means (March 2017–March 2023).

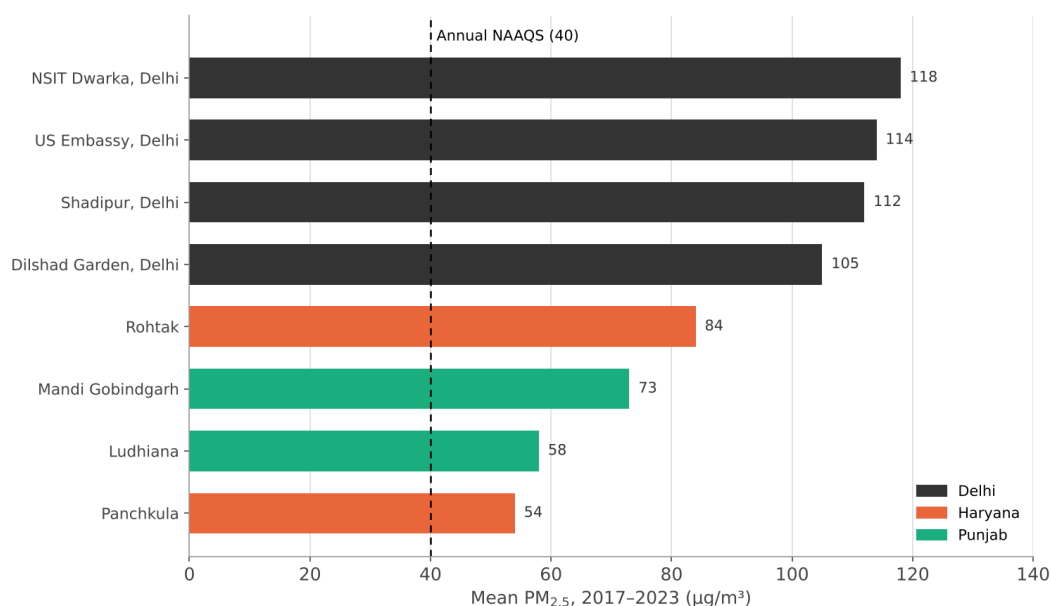


Figure 7. Mean PM_{2.5} at continuous monitoring sites in Delhi, Haryana and Punjab, 2017–2023, against the annual NAAQS. Data: Ghosh et al. [5].

3.7 COVID-19 lockdown as a natural experiment (Punjab and Haryana, 2020)

The 2020 nationwide lockdown reduced transport activity by 50–60%, aviation by 90%, industrial activity by 40% and construction by 70% [13], providing a direct test of how much of northern India's PM is anthropogenic (Table 13, Figures 8 and 9). Across India, modelled PM_{2.5} declined by 26% between the pre-lockdown and lockdown periods, with some of the largest falls in northern India [20]. In Delhi, PM₁₀ and PM_{2.5} were as much as about 60% and 39% below their levels in the same period of 2019, while NO₂ and CO fell by about 53% and 30% relative to the pre-lockdown weeks of 2020 [21], and observed mean PM_{2.5} dropped by 41% to 42.5 µg/m³ [20]. Region-wise analyses found the largest absolute declines in PM_{2.5}, PM₁₀ and NO₂ during the morning (08:00–10:00) and late-evening (20:00–24:00) peak hours, although the percentage reduction was almost constant through the day [22]. In Punjab, mean PM₁₀ and PM_{2.5} decreased by about 45% and 43%, and NAQI by 64.5%, in the first complete-lockdown phase relative to the pre-lockdown period; as restrictions were relaxed, the NAQI reduction shrank to 43%, 35% and 30%. One-way ANOVA showed significant changes ($p < 0.001$) for every pollutant except SO₂ ($p = 0.603$). Strong correlations of PM_{2.5} with NO₂ ($r = 0.92$), NH₃ ($r = 0.95$) and CO ($r = 0.94$) point to shared combustion sources, whereas O₃ rose at several sites because lower NO emissions reduced ozone titration [13].

Haryana showed a similarly large response, measured against the same dates of the previous year rather than the pre-lockdown weeks. Vyas et al. analysed CPCB data for ten parliamentary constituencies, recorded at 15-minute intervals and averaged to daily values, across four lockdown phases (25 March–14 April, 15 April–3 May, 4–17 May and 18–31 May 2020) and the same dates in 2019, 2021 and 2022 [1]. Between lockdown phase 1 (25 March–14 April 2020) and the same window in 2019, mean $PM_{2.5}$ dropped from 75.9 to 32.6 $\mu g/m^3$ (–57%), PM_{10} from 194.5 to 66.9 $\mu g/m^3$ (–66%), NO_x from 34.7 to 12.5 ppb (–64%), O_3 from 45.7 to 23.4 $\mu g/m^3$ (–49%) and CO from 0.83 to 0.58 mg/m^3 (–30%) [1]. District AQI maps for March–May tell the same story: compared with 2019, AQI in 2020 improved by 61–70% in Faridabad (from poor to satisfactory), by 71–80% in Mahendragarh (from moderate to good) and by 51–60% in Karnal, Rohtak and Palwal, but by only 0–10% in Panipat, Charkhi Dadri and Yamunanagar, where AQI remained very poor [14]. The gains did not last: after the lockdown, average $PM_{2.5}$ rose to 54.9 $\mu g/m^3$ in 2021 and 91.3 $\mu g/m^3$ in 2022, and PM_{10} in the 25 March–14 April window had returned to about 195.1 $\mu g/m^3$ by 2022, matching the pre-pandemic level [1]. NO_x also rose again in 2021–2022 but stayed below pre-lockdown values in most phases, whereas CO changed little after the lockdown, suggesting it is less sensitive to short-term changes in activity; $PM_{2.5}$ and NO_x showed the steepest lockdown declines, pointing to transport and industry as their main sources [1]. These observational comparisons were not adjusted for weather, and the Punjab comparison spans the seasonal shift from late winter to spring, when better atmospheric mixing lowers PM levels anyway; modelling work for Delhi has likewise attributed much of the lockdown improvement to favourable meteorology rather than to emission cuts alone [7]. The lockdown declines are therefore best read as an upper estimate of the effect of reduced activity.

Table 13. Changes in air quality during the 2020 COVID-19 lockdown in Punjab and Haryana.

Pollutant	Punjab (lockdown vs pre-lockdown)	Haryana (phase 1 vs same window in 2019)	Haryana, 2022 (after lockdown)
$PM_{2.5}$	$\approx -43\%$ ($p < 0.001$)	75.9 $\rightarrow$ 32.6 $\mu g/m^3$ (–57%)	91.3 $\mu g/m^3$ (post-lockdown average)
PM_{10}	$\approx -45\%$ ($p < 0.001$)	194.5 $\rightarrow$ 66.9 $\mu g/m^3$ (–66%)	195.1 $\mu g/m^3$ (25 Mar–14 Apr; back to 2019 level)
NO_2 / NO_x	–50 to –60% (central region)	34.7 $\rightarrow$ 12.5 ppb (–64%)	Below 2019 in most phases
CO	–50 to –60% (central region)	0.83 $\rightarrow$ 0.58 mg/m^3 (–30%)	Relatively stable
O_3	Increase at several sites	45.7 $\rightarrow$ 23.4 $\mu g/m^3$ (–49%)	–
SO_2	Mixed; not significant ($p = 0.603$)	–	–
NAQI	–64.5% (CL-1); –43%, –35%, –30% (CL-2 to CL-4)	District AQI 0–80% better (Mar–May 2020 vs 2019)	–

Sources: Chaudhry et al. [13]; Vyas et al. [1]; Manjeet et al. [14].

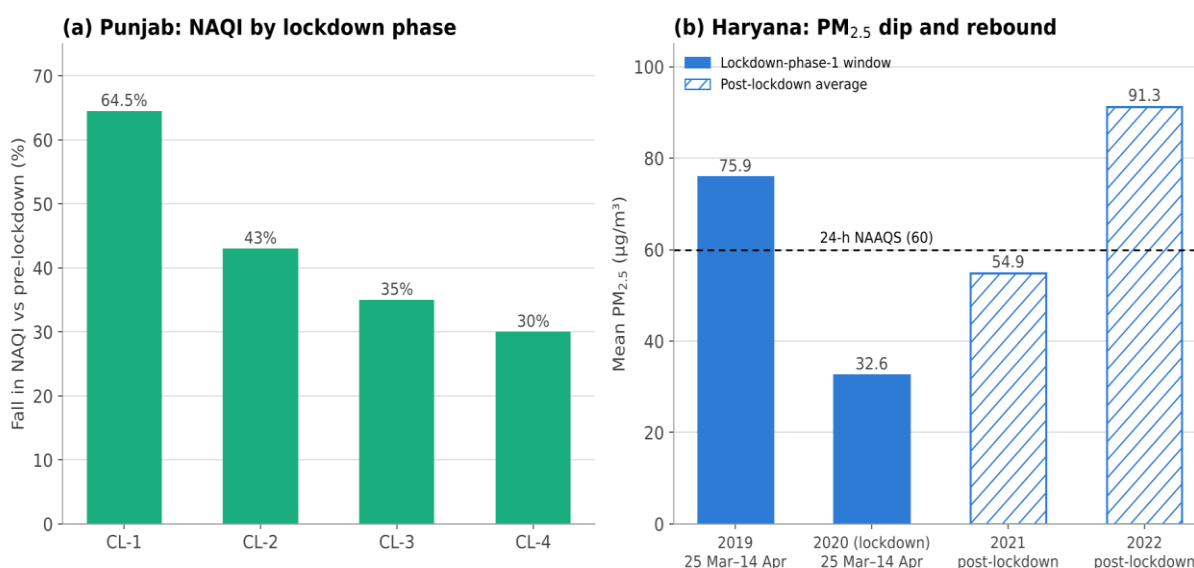


Figure 8. (a) Reduction in Punjab NAQI in the four complete-lockdown phases relative to pre-lockdown; (b) mean $PM_{2.5}$ in Haryana during 25 March–14 April in 2019 and 2020 (lockdown phase 1) and post-lockdown average $PM_{2.5}$ in 2021 and 2022, showing the dip and rebound. Data: Chaudhry et al. [13]; Vyas et al. [1].

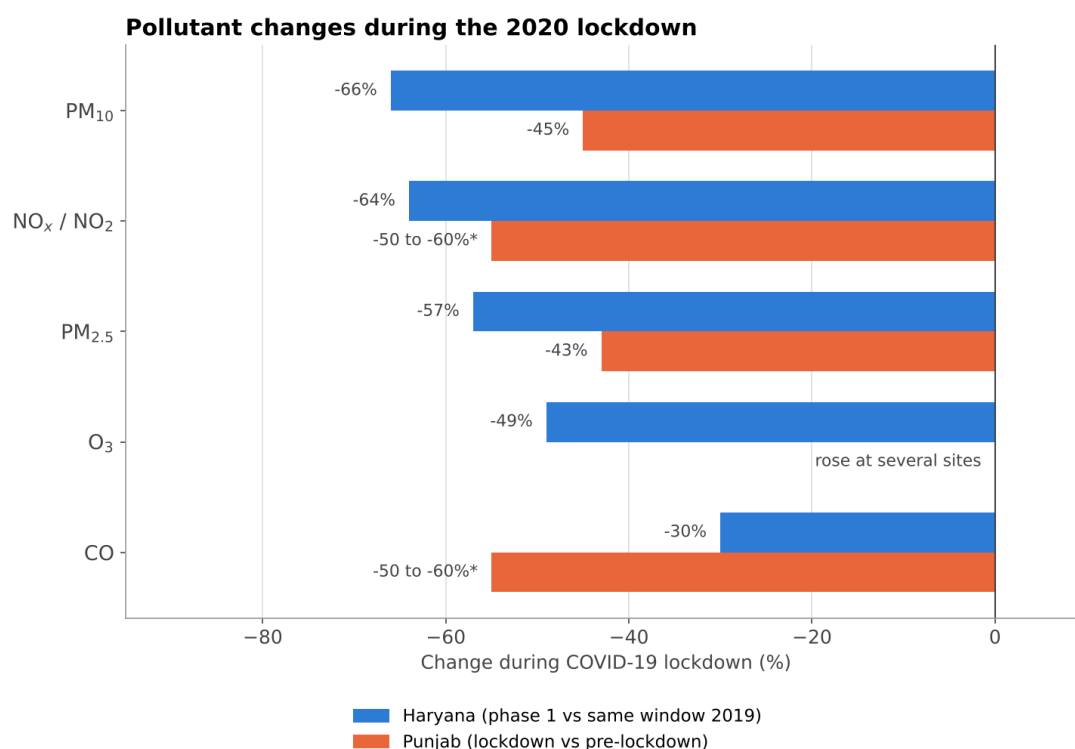


Figure 9. Percentage change in individual pollutants during the 2020 lockdown in Haryana and Punjab. *Punjab NO₂ and CO values are the range reported for the central region (–50 to –60%). Data: Vyas et al. [1]; Chaudhry et al. [13].

3.8 Seasonal patterns across the region

Every dataset reviewed shows a winter maximum and a monsoon minimum (Table 14). Across NCAP cities nationally, mean AQI in January (207 in 2019; 176 in 2023) was well above the annual mean (132 and 113), and winter remained the most polluted season throughout 2019–2023 [11]. In Delhi, mean monthly AQI during 2018–2024 peaked in November (346) and December (332) and was lowest in August (93), a ratio of about 3.7, and the stubble-burning share of PM_{2.5} rose to 15–33% on peak November days in 2023–2024 [4,10]. At the Punjab and Haryana sites, monthly PM_{2.5} peaks in winter and again in April–May during wheat-residue burning, and is lowest in the July–September monsoon [5]. In Chandigarh, PM₁₀ at Sector 25 peaks in October and falls to 34–39 µg/m³ in August–September [15]. In Haryana, low wind speed and winter temperature inversions favour accumulation in densely populated districts, while better mixing in warm seasons aids dispersion [3]. Across northern Indian cities, urban pollutant concentrations are closely linked to temperature, humidity, wind speed and boundary-layer conditions [23].

Table 14. Seasonal peaks, minima and dominant drivers of PM in northern Indian jurisdictions.

Region	Peak period & level	Minimum period & level	Dominant drivers
NCAP cities (national)	Winter: January mean AQI 207 (2019) and 176 (2023)	Monsoon (Jul–Sep); annual mean AQI 132 (2019) and 113 (2023)	Shallow boundary layer, weak circulation; monsoon wet scavenging [4,11]
Delhi	November (mean AQI 346) and December (332), 2018–2024	August (mean AQI 93; ratio ≈ 3.7)	Winter inversions; household, vehicular and NCR sources; upwind crop-residue burning (15–33% of PM _{2.5} on peak November days) [4,7,10]
Punjab	Winter, with a secondary peak in Apr–May (Ludhiana, Mandi Gobindgarh)	Jul–Sep (monsoon)	Paddy- and wheat-residue burning (biomass-burning PC loading 0.8 at Ludhiana); winter inversions; industry [5]
Chandigarh	Oct: PM ₁₀ 121–125 µg/m ³ (Sector 25)	Aug–Sep: 34–39 µg/m ³	Upwind paddy-residue burning; low wind speed; humidity and solar-radiation effects [15]
Haryana	Winter and post-monsoon; secondary Apr–May peak at Rohtak and Panchkula	Monsoon (Jul–Sep)	Inversions, low wind; biomass-smoke transport; NCR traffic and construction [3,5]

4. DISCUSSION

4.1 Spatial patterns: a regional rather than city-specific problem

The evidence shows that high particulate levels are not confined to Delhi. Haryana's NCR hotspots have converged with Delhi [3], and although Punjab's monitored sites are less polluted on average, Ludhiana is the only site in the four jurisdictions where PM_{2.5} is rising significantly [5]. Within Haryana, the NCR districts of Gurugram, Faridabad, Charkhi Dadri, Ballabgarh, Manesar and Bahadurgarh are consistently the most polluted, reflecting emission density, traffic and construction, and in Punjab the town of Mandi Gobindgarh records higher means than Ludhiana [3,5]. Yet even semi-rural, hill and planned locations rarely meet standards: Chandigarh, with its extensive green cover and low industrial base, still exceeded the annual PM₁₀ standard at its Sector 25 station in both years reported (2020–2021) [15]. Because roughly 45% of Haryana's PM originates outside the state [9] and crop-residue burning supplies about 50% of Punjab's and 36% of Haryana's peak-season PM_{2.5} [7], neighbouring NCR districts supplied about 35% of Delhi's pollution in October–November 2024 [10], and Chandigarh's October peaks track paddy-residue burning upwind [15], city-level action alone cannot achieve compliance. Airshed modelling for Delhi confirms this: extending a crop-burning ban from Delhi-NCR to Punjab and Haryana roughly triples its benefit for Delhi's PM_{2.5}, and coordinated multi-sector controls across the airshed achieve about 36% reduction against 24% for the same measures confined to the NCR [7].

4.2 Seasonality and meteorology

The winter maximum is driven by weak regional circulation, shallow boundary layers and temperature inversions that trap emissions near the surface, together with increased biomass and heating fuel use and lower combustion efficiency in cold conditions. In contrast, south-westerly monsoon winds and rain remove particles efficiently in July–August, when Delhi's monthly AQI reaches its annual minimum [4,10]. The post-monsoon period is distinctive in the north-western IGP: paddy-residue burning in Punjab and Haryana coincides with the onset of stagnant conditions, producing the region's sharpest pollution episodes [5,24]. Back-trajectory analysis shows that 69% of air masses reaching Delhi in the post-monsoon season and 73% in winter arrive from the north-west, across Punjab and Haryana [5]. Estimates of the crop-burning share vary widely with method and period [25]. Inverse modelling constrained by a dense sensor network attributed 30–34% of surface PM_{2.5} over Punjab, Haryana and Delhi to crop-residue burning during 1–15 November 2022, rising to 50–56% during plume events [26], whereas another analysis estimated that Punjab burning contributed about 14% of Delhi-NCR PM_{2.5} in October–November 2022 [27]; consistent with this, Delhi's November AQI did not improve between 2021 and 2024 even as paddy-fire counts fell from 71,304 to 9,655 in Punjab and from 6,987 to 1,118 in Haryana [10]. Together these results indicate that stubble burning drives short, intense episodes, while local and other regional sources sustain the high winter baseline.

4.3 Source contributions

Four source groups recur across the studies. (i) Traffic contributes about 30% of annual PM in Punjab [13] and about 13% of PM_{2.5} over Delhi during the 2019–2020 post-monsoon and winter season [7], and dominates NO₂, which fell most sharply during lockdown [1,13]. (ii) Crop-residue burning produces sharp October–November peaks, supplying about 50% of PM_{2.5} in Punjab and 36% in Haryana during the peak burning season [7] and, in a high-density monitoring study of November 2022, about 30–34% of surface PM_{2.5} over Punjab, Haryana and Delhi on average, rising to 50–56% during smoke-plume events [26]. (iii) Industry, thermal power and brick kilns sustain SO₂ and particulate levels even when transport stops, as shown by the absence of a significant SO₂ change during lockdown in Punjab [13]. (iv) Dust and construction – including transported desert dust and NCR construction surges – dominate PM₁₀ [3,4]. Airshed modelling further identifies household solid-fuel combustion as the largest single contributor to PM_{2.5} over Delhi (about 53% during September 2019–January 2020), with secondary aerosol forming more than half of winter PM_{2.5} [7]. The large lockdown declines (about 43% in Punjab and 57% in Haryana, measured against different baselines) indicate that a substantial share of the particulate burden is anthropogenic and therefore controllable, although part of the decline reflects favourable spring meteorology rather than emission cuts alone [1,7].

4.4 Health implications

Measured levels translate into substantial risk. Mean PM_{2.5} of about 51–118 µg/m³ across the jurisdictions reviewed is 10–24 times the WHO guideline [2–5]. PM exposure contributes to COPD, lung cancer, heart disease, stroke and pneumonia, and children and the elderly bear a disproportionate burden [3,6]. In Delhi, an analysis of daily data from 11 monitoring stations and a major referral hospital found that respiratory hospital visits peaked in winter and autumn and rose by 0.21% for every 10 µg/m³ increase in PM₁₀ (cumulative lag 0–6 days) and by 32.6% for every 10 µg/m³ increase in same-day SO₂; although that study covers 2016–2018, its mean PM_{2.5} (107 µg/m³) and PM₁₀ (211 µg/m³) are similar to the levels recorded during 2018–2024 [12]. Real-time survey evidence from Delhi in January 2025, when daily PM_{2.5} exceeded 170 µg/m³, showed roughly twofold higher reporting of itchy eyes and of diarrhoea or vomiting, more respiratory difficulty and low mood, and more missed school, work and healthcare appointments among children, young people and parents than on a good-air day [6].

4.5 Policy landscape and effectiveness

India's framework includes the Air (Prevention and Control of Pollution) Act 1981, the NAAQS (2009), the Graded Response Action Plan (GRAP) for Delhi-NCR (2017), Bharat Stage VI vehicle norms (2020), the National Clean Air Programme (NCAP, 2019) and state winter action plans [4,8,9,28]. NCAP targeted a 20–30% reduction in PM_{2.5} across 131 non-attainment cities by 2024 [7], and attainment of the annual PM₁₀ standard of 60 µg/m³ has since been used as an alternative target [11]. For crop burning, modelling suggests that simply shifting burning in Punjab two hours earlier could avert roughly 10,000 deaths a year [29], and the weakening link between fire counts and Delhi PM_{2.5} has been partly credited to GRAP [27]. Subsidised in-situ residue-management machinery (more than 117,000 machines in Punjab and 80,000 in Haryana by October 2023, under a ₹3,333 crore Crop Residue Management Scheme) accompanied the steep

fall in fire counts after 2021, and 1,727 Delhi industries had switched to piped natural gas, yet Delhi's AQI showed no clear response [10]. The decline in Delhi's PM_{2.5} and PM₁₀ between 2018 and 2023 and the rise in “good” to “moderate” AQI days to 209 in 2024 suggest that vehicle, fuel and dust measures are having some effect [4]; Delhi's 25-point Air Pollution Mitigation Plan 2025 extends these to road dust, end-of-life vehicles, industry, waste, construction and demolition, greening and monitoring [4]. However, the renewed rise in Delhi's PM in 2024, the near-absence of change in Delhi's annual PM_{2.5} between 2019 and 2023 (105.1 and 103.3 µg/m³) and in the share of NCAP cities above 150 µg/m³ PM₁₀, the significant rise at Ludhiana and the post-lockdown rebound in Haryana show that progress remains insufficient [1,4,5,11]. Chandigarh's persistent PM₁₀ exceedances despite these measures illustrate the same point: airshed-level coordination through the Commission for Air Quality Management across Delhi, Haryana, Punjab and Chandigarh is as important as local action.

4.6 Limitations of the evidence and research gaps

Urban bias in monitoring. Continuous stations are almost exclusively urban; rural areas with significant crop-residue and household emissions are largely unmonitored, and most NCAP cities operate only a single station [7,11].

Short and uneven records. Many networks expanded only after 2019 (for example, Haryana's continuous network grew from 24 to 30 stations between 2019 and 2023, while Punjab's stayed at 8), so few stations provide continuous records across 2018–2024, and many Haryana districts lack data for some years [3,11].

Partial-year and short-period Delhi data. The CPCB averages available for Delhi for 2018–2024 cover 1 January–18 November and therefore understate annual means, and the Delhi source shares come from a three-week campaign period (October–November 2024) or a single modelled season (September 2019–January 2020) [4,7,10].

Inconsistent datasets. Haryana district compilations contain implausible jumps (e.g., Panchkula 145 → 30 µg/m³ PM_{2.5} between 2019 and 2020), reported state averages do not always match district values (103 versus 61 µg/m³ PM_{2.5} in 2024), and district PM_{2.5} and PM₁₀ are uncorrelated ($r = -0.06$), which is implausible for co-located measurements [3].

Limited fine-particle data in smaller cities. Chandigarh's records in the reviewed sources are limited to PM₁₀ at a single continuous station for 2020–2021 [15].

Uncertain crop-burning attribution. Published estimates of the stubble-burning share of Delhi-NCR PM_{2.5} range from about 14% to more than 50% depending on method, period and whether plume events are included [25–27].

Meteorology and source apportionment. Most state-level studies did not adjust for meteorology or perform source apportionment, so the attribution of trends to policy remains partly qualitative [1,3].

5. Measures to Control Outdoor Particulate Pollution

The evidence points to the measures summarised in Table 15.

Table 15. Recommended measures to reduce ambient particulate pollution in northern Indian states.

Level	Measure	Expected benefit
Regional / airshed	Coordinate action across Delhi-NCR, Haryana, Punjab and Chandigarh through CAQM, GRAP and winter action plans [4,9]	Addresses the large transboundary share of PM
	Provide alternatives to stubble burning: in-situ residue management, subsidies, enforcement and better timing of any residual burning [1,10,29]	Smaller October–November peaks
	Expand continuous monitoring to smaller towns and rural areas, with real-time public alerts [1,11]	Better exposure assessment and targeting
City / state	Enforce NCAP city action plans with transparent reporting [28]	Lower annual PM _{2.5} and PM ₁₀
	Promote electric vehicles and public transport, phase out old vehicles, improve traffic management [1]	Reduced exhaust PM _{2.5} and NO ₂
	Install continuous emission monitoring and stricter norms in industrial clusters, power plants and brick kilns [1,4]	Reduced industrial PM and SO ₂
	Control construction and road dust (covering, wet suppression, paved shoulders); expand green cover [3,4]	Lower PM ₁₀
	Stop open burning of municipal waste and remediate legacy landfills [4]	Fewer local PM hotspots
Public	Promote clean mobility and joint air-quality planning across the Chandigarh–Mohali–Panchkula tricity [15]	Reduced traffic PM and NO ₂ across the tricity
	Health advisories and awareness campaigns during winter episodes [6]	Reduced exposure for vulnerable groups

6. CONCLUSIONS

Outdoor particulate pollution in northern Indian cities remains far above national standards and WHO guidelines. The evidence published between 2018 and 2026 supports seven conclusions.

1. Across the jurisdictions reviewed, mean PM_{2.5} (about 51–118 µg/m³) and PM₁₀ (about 76–225 µg/m³) were 1.3–3.0 and 1.3–3.8 times the national standards, and no city, district or network mean met either annual standard.
2. Delhi's PM_{2.5} (83–101 µg/m³ as January–November means in 2018–2024; 95–108 µg/m³ as annual means in 2019–2024) and PM₁₀ (164–225 µg/m³) improved only modestly after 2018 and rose again in 2024; the city still records 157–206 “poor” to “severe” AQI days a year, and modelling shows that airshed-wide, multi-sector action is needed for substantial reductions.
3. Punjab's continuous sites (58–73 µg/m³ PM_{2.5}, 2017–2023) are less polluted than Delhi on average, but Ludhiana shows a significant rise of almost 10% a year, and crop-residue burning supplies about half of Punjab's PM_{2.5} in the peak burning season.
4. Haryana's district data average about 64 µg/m³ PM_{2.5} and 145 µg/m³ PM₁₀ (2019–2024); the NCR hotspots of Gurugram, Faridabad and Charkhi Dadri (85–95 µg/m³) now rival Delhi.
5. Chandigarh, despite its planned layout and green cover, exceeded the annual PM₁₀ standard at its Sector 25 station in 2020 and 2021 (76.2 and 91.7 µg/m³), with October peaks linked to upwind stubble burning.
6. The 2020 lockdown cut PM_{2.5} by about 43% in Punjab (against the pre-lockdown weeks) and 57% in Haryana (against the same period of 2019), which indicates that a large share of the burden is anthropogenic, although meteorology also contributed; moreover, Haryana's PM₁₀ had returned to its pre-pandemic level within two years.
7. Because a large share of PM in each jurisdiction is transported from elsewhere, sustained improvement requires airshed-wide coordination, alternatives to stubble burning, strict enforcement of NCAP plans and expanded monitoring beyond large cities.

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Conflict of Interest

The authors declare no conflict of interest.

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